# Calcareous soils, their properties and potential limitations to conifer growth in southeastern British Columbia and western Alberta: a literature review

*B.E. Kishchuk*

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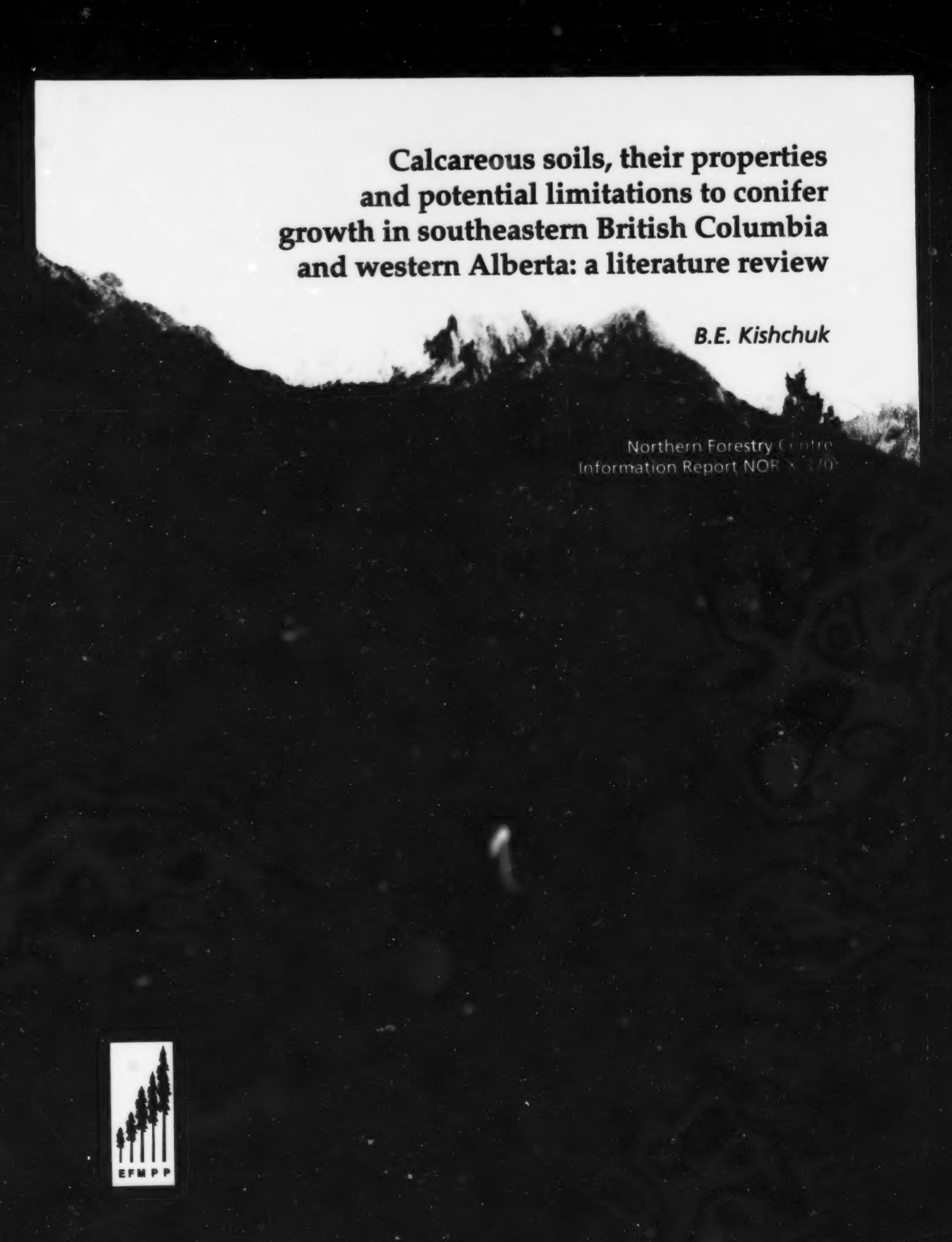

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**Cover photo:**

Dry Creek, a tributary of the Kootenay River, about 15 km east of Canal Flats, British Columbia. Photo by Mike Curran, B.C. Ministry of Forests.

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# CALCAREOUS SOILS, THEIR PROPERTIES AND POTENTIAL LIMITATIONS TO CONIFER GROWTH IN SOUTHEASTERN BRITISH COLUMBIA AND WESTERN ALBERTA: A LITERATURE REVIEW

*B.E. Kishchuk*

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## ABSTRACT

This report is a review of published literature on calcareous soils and their role in the productivity of coniferous forests in southwestern British Columbia and western Alberta. Definitions, origins, and properties of calcareous soils are described. Processes contributing to growth limitations on calcareous soils are reviewed. Chemical properties of calcareous soils may give rise to tree nutrition problems or other metabolic disturbances. Physical properties of calcareous soils may also affect tree growth through compacting or cementing effects. Factors controlling productivity on calcareous soils are discussed with particular reference to coniferous species in western Canada. Depth to carbonates in the soil profile appears to be an important factor in the establishment and productivity of coniferous stands in western Canada. Forest practices resulting in displacement of calcareous subsoils and implications of calcareous soil displacement are identified. Although instances where decreases in forest productivity on calcareous soils have been identified, calcareous soils do not appear to have a consistently adverse effect on productivity. Attributes of soils and other site factors must be identified to determine the role of calcareous soils in stand establishment and productivity.

## RÉSUMÉ

Le présent rapport passe en revue la documentation publiée sur les sols calcaires et leur rôle dans la productivité des forêts de conifères du Sud-Ouest de la Colombie-Britannique et de l'Ouest de l'Alberta. Il définit les sols calcaires et précise leurs origines et leurs propriétés. Il examine les processus contribuant à limiter la croissance sur ce type de sol. Les propriétés chimiques des sols calcaires peuvent provoquer des déséquilibres nutritionnels des forêts ou d'autres troubles métaboliques. Les propriétés physiques des sols calcaires, qui sont plus sensibles au compactage et à la cimentation, peuvent également affecter la croissance des arbres. Ce rapport examine les facteurs régissant la productivité des arbres poussant dans des sols calcaires, notamment des essences de conifères de l'Ouest du Canada. Il semble que la profondeur à laquelle se trouvent les carbonates dans le profil de sol joue un rôle important dans l'établissement et la productivité des peuplements de conifères de l'Ouest du Canada. Ce rapport précise les pratiques forestières entraînant un déplacement du sous-sol calcaire et les incidences de ce déplacement. Même si des cas de réduction de la productivité des forêts poussant dans des sols calcaires ont déjà été observés, il semble que ce type de sol n'a pas systématiquement un effet défavorable sur la productivité. Il faut définir les caractéristiques des sols et d'autres facteurs stationnels afin de déterminer le rôle des sols calcaires dans l'établissement et la productivité des peuplements.

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**NOTE**

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# INTRODUCTION

As pressure on forested lands becomes more intense it becomes increasingly important to understand the limitations to productivity imposed by particular site and soil conditions. Calcareous, or lime-rich, soils may pose limitations to tree growth and productivity because of chemical and physical properties. These soils contain calcium or magnesium carbonates. Calcareous soils may affect productivity both in undisturbed soils and in soils disturbed as a result of forest practices. Calcareous soils are of interest in southeastern British Columbia (B.C.) and western Alberta where they are associated with impaired regeneration and growth of conifers.

Attribution of poor establishment and growth of conifers to calcareous soils is largely based on field observation and anecdotal reports. Documented evidence of poor conifer performance on calcareous soils in the literature is limited. Controlled studies of conifer growth on calcareous and non-calcareous soils are lacking, and mechanisms for poor performance have not been systematically investigated. This review of published literature was undertaken to determine the state of our understanding of calcareous soils and the mechanisms by which coniferous forest productivity in southeastern B.C. and western Alberta may be affected. The focus of this report is on calcareous soils in western Canada and their role in the productivity of coniferous forests. Material has been drawn from other locations and tree species to provide background information on soil and plant processes. The material reviewed was limited to properties of soil and foliage on naturally occurring calcareous soils, and did not encompass studies where lime was added as an amendment. This review will outline the properties of calcareous soils, potential mechanisms for nutritional problems and growth reduction, factors correlated with the productivity of conifers on calcareous soils, and implications of forest harvesting-based disturbance on calcareous soils.

# PROPERTIES OF CALCAREOUS SOILS

## Recognition of Calcareous Soils

Calcareous soils effervesce or fizz when dilute hydrochloric acid (HCl, muriatic acid) is applied (Agriculture Canada 1976; Soil Science Society of America 1997). Calcareous soils are sometimes referred to as alkaline (high pH) soils, but they are distinguishable from other soils with high pH. Calcareous soils contain carbonates of the alkaline earth metals calcium (Ca) and magnesium (Mg), and to a lesser degree, carbonates of the transition metals iron (Fe), zinc (Zn), and manganese (Mn) (Brown et al. 1978; Talibudeen 1981). Calcite and aragonite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and magnesite ($MgCO_3$) are the calcium and magnesium carbonate minerals found in calcareous soils. They are mainly present as calcite, and to a lesser extent as dolomite (Hunt 1972; Brown et al. 1978). The carbonate minerals may be either primary carbonates originating from carbonate-rich parent materials, or secondary carbonates formed by partial re-precipitation of dissolved carbonates. The pH range of calcareous soils (determined in water) is from 7.0 to 8.5 (Yaalon 1957).

Calcareous soils are distinguished from saline soils, which contain high concentrations of neutral salts more soluble than Ca and Mg carbonates (Soil Classification Working Group 1998). Not all saline soils have high pH. Examples of salts associated with saline soils are the sulfate salts sodium sulfate ($Na_2SO_4$), magnesium sulfate ($MgSO_4$), calcium sulfate or gypsum ($CaSO_4$), and the chloride salts sodium chloride (NaCl) and magnesium chloride ($MgCl_2$). The degree of salinity is determined by the electrical conductivity of the soil solution. Alkali or sodic soils contain sodium carbonate ($Na_2CO_3$) and have pH values >8.5 (Russell 1973). Soils with pH greater than 7.0 (neutral pH) are alkaline, thus calcareous soils, some saline soils, and sodic soils are alkaline. The dominance of Ca and Mg carbonates in calcareous soils, soluble salts in saline soils, and Na in sodic soils separate these groups.

The *Canadian System of Soil Classification* does not specifically recognize soils formed under the influence of Ca or carbonate-rich parent materials at the Sub-group level (Soil Classification Working Group 1998). Carbonates are indicated in soil descriptions by the suffixes "k", which indicates the presence of carbonates (for example, Bmk or Ck horizons), or "ca" indicating accumulation of secondary carbonates (for example, Cca horizons).

Calcareous soils containing sufficient carbonates within the rooting zone to limit growth through chemical or physical properties are of concern to conifer productivity.

The common field test for the presence of carbonates in soils is the application of dilute hydrochloric acid (10% HCl) to the fine fraction (<2 mm) of the soil. Effervescence (fizz, bubbling, foaming, or hissing) on contact of acid with the soil indicates the presence of carbonates. Calcium carbonates are more reactive than Mg carbonates in this test, and sufficient time must be allowed for the reaction of Mg carbonates (Day 1983). The degree of effervescence is noted, and effervescence classes based on the degree of the acid reaction are determined (Table 1) (Day 1983; Luttmerding et al. 1990).

The actual carbonate content, expressed as the $CaCO_3$ equivalent, must be determined by laboratory analysis (Appendix 1). However, estimates of the $CaCO_3$ equivalent may be made from the effervescence classes (Kalra and Maynard 1991; Table 1). Calcareousness classes may be designated on the basis of the $CaCO_3$ equivalent (Day 1983; Table 1). Soils with less than 1% $CaCO_3$ equivalent would not effervesce sufficiently with acid and would not be considered calcareous.

The *Hazard Assessment Keys for Evaluating Site Sensitivity to Soil Degrading Processes* (British Columbia Ministry of Forests 1995) use the presence of appreciable carbonates as a criterion for assessing soil and forest floor displacement hazards. Soils forming a low foam in reaction with acid (classified as moderately strong effervescence) contain sufficient carbonates to be considered an unfavorable substrate for plant growth in the southern interior of B.C. (Curran et al. 1997). A $CaCO_3$ equivalent of about 5–15% can be inferred for soils with moderate to strong effervescence from Table 1. This has been confirmed from observations from southeastern B.C. Soils near Golden, B.C. that showed moderate to strong effervescence had $CaCO_3$ equivalents of 4–8% (Smith and Wass 1994a), and soils near Invermere, B.C. with strong effervescence had $CaCO_3$ equivalents of 6–9% (Kishchuk et al. 1999).

## Origin and Development of Calcareous Soils

The source of primary carbonate minerals in most soils is marine limestone or dolomitic limestone deposits (Salomons and Mook 1976). Limestone is sedimentary rock containing primarily $CaCO_3$, while dolomitic limestone refers to deposits containing both $CaCO_3$ and dolomite (Hunt 1972). Carbonate parent materials are mineralogically quite uniform, varying only in the presence and quantity of cations other than Ca and in clay content (Kinzel 1983).

Calcareous soils develop on a variety of carbonate-rich parent materials, including surficial deposits (for example, glacial till, glaciolacustrine, and eolian) and limestone bedrock (rendzina soils). Extensive areas of calcareous soils in southeastern

**Table 1. Soil reaction with 10% HCl, effervescence class, $CaCO_3$ equivalent, and calcareousness class**

| Reaction[a] | Effervescence class[b] | $CaCO_3$ equivalent (%) | | Calcareousness class[d] |
|---|---|---|---|---|
| | | Kalra and Maynard (1991) | Day (1983) | |
| No reaction | None | 0 | <5 | Weakly calcareous |
| Few bubbles | Very weak | n.d.[c] | 5–15 | Moderately calcareous |
| Bubbles readily observed | Weak | 1–5 | 15–25 | Strongly calcareous |
| Bubbles form low foam | Moderate | 6–10 | 25–40 | Very strongly calcareous |
| Bubbles form thick foam | Strong | >10 | >40 | Extremely calcareous |

[a] Day 1983; Luttmerding et al. 1999.

[b] Day 1983; Luttmerding et al. 1990.

[c] n.d. = not determined.

[d] Day 1983.

British Columbia and western Alberta supporting coniferous forests have been influenced by the limestone bedrock of the Rocky Mountains and redistributed glacial drift (Dumanski et al. 1972; Wittneben and Lacelle 1986; Lacelle 1990). Soils developed on calcareous loess have also been described in west-central Alberta (Dumanski and Pawluk 1971; Dumanski et al. 1972). Rendzina soils are rare in Canada but have been identified in the Ogilvie Mountains of the Yukon Territory (Schreier and Lavkulich 1985).

Soils containing carbonates within the rooting zone have likely developed on calcareous parent materials, with or without secondary carbonate accumulation, that have not undergone sufficient weathering and leaching to degrade the carbonate minerals and remove their products from the rooting zone. Limited precipitation has contributed to the development of shallow profiles on calcareous parent materials in southeastern B.C. (Lacelle 1990). Weak soil development and non-acidic surface horizons are reflected in the classification of many forest soils developing on calcareous parent materials as Eutric Brunisols.

The dissolution and partial re-precipitation of carbonate minerals are the dominant processes in calcareous soils (Talibudeen 1981; Dutil 1982). Soil development on calcareous parent materials is controlled by the dissolution, re-precipitation, and leaching of carbonates and their products (Lelong and Souchier 1982; van Breeman and Protz 1988). Calcareous soils are highly buffered and remain in the $CaCO_3$ buffering range of pH until all carbonate is removed from the fine fraction and weathering of silicate minerals and associated acidification begins (Ulrich 1983; Loeppert 1986). The soil solution and cation exchange complex of calcareous soils is dominated by Ca (Ulrich 1983). Magnesium is more readily leached from dolomite-derived soils than Ca (Dutil 1982).

Soil texture also plays a role in profile development. There is an inverse relationship between soil clay content and degree of development on calcareous parent materials (Matthews et al. 1955). Finely divided carbonates further limit clay translocation and soil development (Richardson 1989). The development of acidic horizons on calcareous parent materials occurs slowly. Formation of podzolic soil profiles on coarse-textured calcareous parent materials in Ontario was estimated to take 2300 years (Protz et al. 1984). Localized development of podzolic horizons may occur in association with Fe-containing carbonate minerals in calcareous eolian deposits (Smith et al. 1983).

Accumulation of secondary carbonates occurs in soils still containing significant quantities of primary carbonates (Dutil 1982). All of the carbonates in surface horizons of soils formed on calcareous parent materials may be recently formed from the weathering and re-precipitation of carbonates (Salomons and Mook 1976). Dissolved carbonates may be leached downward in the profile, or may move upward with a rising water table (Beckwith and Hansen 1982; Birkeland 1984). Original and pedogenetic carbonates are difficult to separate, particularly where secondary carbonates are fine textured. Large secondary carbonates (for example, concretions or filaments) are morphologically quite distinct. Secondary carbonate development in the soil matrix has been described (Gile et al. 1966; Birkeland 1984; Schaetzl et al. 1996), and field assessment of secondary carbonates is described in Luttmerding et al. (1990).

## Carbonate Chemistry

The chemical conditions of calcareous soils are dominated by the presence of $CaCO_3$ (Loeppert 1986). The overall reaction for the dissolution and re-precipitation of $CaCO_3$ is

$$CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{2+} + 2\,HCO_3^-.$$

A more detailed breakdown of the reaction and the factors controlling carbonate dissolution and precipitation are given in Appendix 1.

Calcium and Mg carbonates are among the least stable, or most reactive, soil constituents (Hunt 1972). Carbonates are found in the sand (2000–50 $\mu$m), silt (50–2 $\mu$m), and clay (<2 $\mu$m) fractions of soil (Thorne and Seatz 1955). Carbonates in the clay and fine silt (2–5 $\mu$m) fractions are most reactive (Moore et al. 1990) and are associated with plant nutrition problems on calcareous soils (Yaalon 1957; Carter 1981). Carbonate reactivity may be a more useful measure of the effects of carbonates on soil processes than total carbonate content alone (Loeppert et al. 1994). The reactivity of carbonates in calcareous soils is controlled by particle size distribution, mineralogy, surface morphology, and aggregation of carbonates with other soil components (Hartwig and Loeppert 1991). An overview of methods for determining carbonate reactivity and carbonate content of soils is given in Appendix 2.

## Soil Chemical and Nutritional Limitations

### Soil Organic Matter Stabilization

Soil organic matter dynamics in calcareous soils under coniferous species have not been systematically examined. Most of the available information on relationships between calcareous soils and soil organic matter comes from European literature on hardwood species. Specifically, relationships among species found on calcareous soils (beech and other hardwoods), conditions for soil fauna and microbial decomposers, and the development of mull humus forms have been investigated (Ulrich 1983; Muys 1995). Calcareous parent materials may have a greater effect on humus form and stable organic matter formation than on the vegetation (Toutain and Duchaufour 1970; Oyanarte et al. 1994).

Calcareous soils may be associated with higher soil organic matter contents than non-calcareous soils (Oades 1988). Decomposition may initially be faster on calcareous soils than non-calcareous soils (Oades 1988). This is in part due to the polymerization by Ca of plant polyphenols that increase the resistance of foliar litter to decomposition (Ulrich 1983; Carlyle 1986). However, mixing of the fine organic particles with mineral soil constituents slows further decomposition through the formation of Ca and Mg bridges between clay particles, organic molecules, and microbial biomass (Oades 1988). More organic matter is stabilized and retained in alkaline Ca-saturated soils than in slightly acidic soils (Oades 1995).

Calcium inputs in litter are greater on calcareous than non-calcareous soils (Pape et al. 1989), which may create negative feedback for organic matter decomposition. Soil decomposer activity (*Isopoda*) was found to be greater in litter from calcareous soils than non-calcareous soils (Nicolai 1988), likely resulting in greater soil mixing.

Soil organic matter is also stabilized and physically protected from decomposition by coatings of $CaCO_3$ on organic matter (le Tacon 1978), and by cementation of soil aggregates with $CaCO_3$ (Oyanarte et al. 1994). Persistent carbonate-organic matter coatings may form on coarse fragments and stabilize a substantial portion of the soil organic matter (Schaetzl 1991).

### Nutritional Limitations

Classification of plant species tolerance or avoidance of calcareous soils in the ecological literature (calcicole and calcifuge plants, respectively) initially focussed on plant response directly to pH and high soil Ca concentrations. However, clear relationships between these properties and species distribution have not been demonstrated (Burström 1968; Kinzel 1983). More complex nutritional mechanisms may be involved. In addition, there is likely a continuum of species tolerance to calcareous soils, rather than sharp delineations (Burström 1968).

The presence of carbonates in calcareous soils controls several aspects of nutrient availability (Talibudeen 1981; Bui et al. 1990). Chemical properties influencing nutrient availability on calcareous soils are high pH and high concentrations of bicarbonate ($HCO_3^-$) and $Ca^{2+}$ ions in the soil solution. Nutritional and physiological problems in trees growing on calcareous soils may be related either to high concentrations of carbonate or bicarbonate ions, or to deficient or excess nutrient elements. High carbonate ion ($CO_3^{2-}$) concentrations may have an adverse effect on seedling emergence and growth (Maynard et al. 1997), as well as on mycorrhizal development (Lapeyrie and Bruchet 1986).

Examples of nutrient deficiencies in tree species on calcareous soils are shown in Table 2. Nutrient deficiencies in these studies were diagnosed either by foliar nutrient concentrations or by response to nutrient applications. Despite the number of potential nutritional problems in trees growing on calcareous soils, very few instances have been documented in the literature.

Research trials to specifically address nutritional problems in conifers on calcareous soils in southeastern B.C. have recently been undertaken (Curran 1999). Specific nutritional problems are discussed further.

#### *Iron*

Iron is the most commonly deficient nutrient on calcareous soils. The manifestation of Fe deficiency on calcareous soils has been recognized as Fe-chlorosis, lime-induced chlorosis, or lime-chlorosis. All plants

**Table 2. Nutrient deficiencies identified in tree species on calcareous soils**

| Species | Location | Nutrient | Reference |
|---|---|---|---|
| *Pinus resinosa* | Ontario, Canada | Iron, manganese | Ellis and Whitney 1975 |
| *Pinus radiata* | South Australia<br>Victoria, Australia | Manganese, zinc, copper | Ruiter 1983 |
| *Pinus sylvestris* | France | Iron, manganese | Duchaufour 1960 |
| *Picea excelsa* | France | Iron, manganese | Duchaufour 1960 |
| *Populus tremuloides* | Manitoba, Canada | Iron, manganese | Wall et al. 1971 |
| *Quercus palustris* | Illinois, USA | Iron | Schoeneweiss 1973 |
| *Eucalyptus* spp. | Victoria, Australia | Iron | Stewart et al. 1981 |

growing on calcareous soils are susceptible to Fe-chlorosis, but vary in their tolerance to it (Loeppert et al. 1994). There are several environmental and soil chemical conditions contributing to Fe-chlorosis (Chaney 1984), but a definitive soil-based cause has not been established (Chen and Barak 1982).

Low Fe availability on calcareous soils results from low concentrations of dissolved inorganic Fe at the pH range of calcareous soils (Lindsay and Schwab 1982), and the reaction of Fe with $CaCO_3$ forming insoluble Fe-oxides (Loeppert et al. 1984). Mechanisms by which Fe availability may be increased are the formation of Fe-chelates, rhizosphere acidification, and alteration of rhizosphere redox conditions (Lindsay and Schwab 1982; Uren 1984; Loeppert 1986; Marschner et al. 1989). Iron availability in alkaline soils may also be increased by ectomycorrhizal hydroxamate siderophore Fe-chelators (Szaniszlo et al. 1981; Powell et al. 1982; Perry et al. 1984).

The distribution of Fe within the chloroplasts of Fe-chlorotic foliage is altered such that not all of the Fe is active in chlorophyll synthesis and a portion remains metabolically inactive (Marschner 1995). The resulting chlorosis is the identifying symptom of Fe-deficiency. The inactivation of Fe by phosphorus (P) (Anderson 1982) or by other cations has been hypothesized, but Fe-P precipitates have not been identified in Fe-chlorotic plants (Mazzolini et al. 1982). Fractions of total foliar Fe, including measures of active Fe in tissue may be useful in the diagnosis of Fe-chlorosis (Chaney 1984). Water deficits in Fe-chlorotic plants are correlated with loss of stomatal function and decreased chlorophyll content (Hutchinson 1970; Anderson 1984).

### *Other Micronutrients*

Decreased availability of soil Mn, Zn, copper (Cu), and boron (B) are also associated with calcareous soils (Talibudeen 1981; Marschner 1995). Decreased availability of these elements results from both pH effects and interactions with soil carbonates. Similarly to Fe, inorganic Mn and Zn are less soluble in the alkaline range of pH, and are precipitated as carbonate minerals (Thorne and Seatz 1955; Marschner 1995). Manganese, Zn, and Cu also undergo adsorption reactions with $CaCO_3$ minerals (Udo et al. 1970; Mesquita and Vieira e Silva 1996), decreasing both the availability of the micronutrients and the reactivity of the $CaCO_3$ (Talibudeen 1981). Chelates of Mn, Zn, and Cu have been used to increase micronutrient availability on calcareous soils (Ryan and Hariq 1983). The pH-dependent availability of B is more complex than that of the micronutrient cations and may be more difficult to predict (Thorne and Seatz 1955; Peterson and Newman 1976). Methodology for the determination of micronutrients in calcareous soils is under development (Quevauviller et al. 1996).

### *Phosphorus*

The predominant mechanism for low P availability on calcareous soils is the surface adsorptive reaction of phosphate ions with carbonate minerals (Thorne and Seatz 1955; Talibudeen 1981). At the pH of calcareous soils, phosphate is present mainly as the secondary orthophosphate ion ($HPO_4^{2-}$). A second, possibly subsequent, mechanism for low P availability is the formation of insoluble Ca–$PO_4$ minerals (Talibudeen 1981; Kinzel 1983; Marion et al 1993), a reaction favored by high soil Ca concentrations (Gilmore and Matis 1981). Phosphate

deficiencies on calcareous soils likely occur in plants with relatively poor P uptake capacity (Kinzel 1983). Mycorrhizal associations may increase P uptake on calcareous soils (Lapeyrie and Chilvers 1985). A proposed mechanism for increased P availability by mycorrhizal fungi is the secretion of organic acids, dissolution of carbonate minerals, and precipitation of Ca-oxalate on the fungal hyphae (Malajczuk and Cromack 1982; Callot et al. 1985). Mycorrhizal associations have been shown to improve the nutritional status and growth of pines on calcareous soils (Dale et al. 1955; Lapeyrie 1990).

#### *Nitrogen*

Nitrogen (N) nutrition problems on calcareous soils are associated with increased soil nitrate levels. Nitrification in forest soils has been shown to increase where pH has been increased with the addition of $CaCO_3$, wood ash, or other basic amendments (Martikainen 1984; Sahrawat et al. 1985; von Mersi et al. 1992; Priha and Smolander 1995). Most studies examining pH effects on nitrification have involved the addition of basic amendments to acidic substrates, with variable and short-lived results (Popović 1975; Fog 1988). There have been few comparisons of nitrification on calcareous and non-calcareous soils. The available information indicates that nitrification rates were greater on calcareous soils (Nakos 1979a, 1984; Stams and Marnette 1990; Stams et al. 1990), or the same as on non-calcareous soils (le Tacon 1978). The effects of $CaCO_3$ on nitrification are often not clearly separated from effects on decomposition or N mineralization (Robertson 1982). Soil pH alone is likely not the controlling factor for nitrification in coniferous forest soils (Killham 1990; van Miegroet and Johnson 1993).

One aspect of N nutrition on calcareous soils involves amino acid accumulation in plant tissue (Clement et al. 1977). Elevated concentrations of organic acids and organic anions have been observed in plants growing on calcareous soils (Nakos 1979b; Carter 1980, 1987). Organic acid accumulation is associated with disturbed carbon metabolism in Fe-chlorotic plants (Iljin 1951). Accumulation of amino acids likely results both from an accumulation of organic acids and high levels of available N as nitrate (Kinzel 1983). Protein synthesis is depressed under conditions of Fe-chlorosis (Marschner 1995), preventing further metabolism of the accumulating amino acids.

Another role of N in nutritional disturbances is in the ammonium/nitrate ($NH_4^+/NO_3^-$) uptake balance (Chen and Barak 1982). Where N uptake is predominantly as $NO_3^-$, cation uptake is increased, with cations accumulating in tissue (van den Driessche 1978; Carter 1980). Cations such as Ca may play a role in the inactivation of Fe within foliar tissue and prevention of Fe translocation (Nakos 1979b). Uptake of N as $NO_3^-$ maintains high rhizosphere pH (Kinzel 1983), and low availability of micronutrients may be exacerbated.

#### *Calcium/Potassium Imbalances*

High soil solution concentrations of Ca may result in decreased potassium (K) uptake (Thorne and Seatz 1955). Imbalances in Ca/K ion uptake and Ca induced K deficiencies may occur on both calcareous (Clement et al. 1977; Ulrich 1983; Bonneau 1992) and limed soils (Gilmore 1972). Possible K deficiencies in Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) foliage with elevated foliar Ca concentrations were observed on calcareous soils in southeastern B.C. (Smith and Wass 1994a).

### Soil Physical Limitations

Carbonates influence the physical properties of soils both at the level of soil horizons and soil aggregates. The poor physical properties of many interior B.C. subsoils, for example high bulk density and low macroporosity (Lewis et al. 1991), are likely to be compounded by the fine textures and the cementing action of calcareous materials (Curran 1999). Calcareous soils may be compacted or cemented at depth (Lavagne and Moutte 1963; Utzig and Herring 1975), and may form surface crusts that may inhibit seedling emergence and growth (Hager and Seighardt 1984; Tinus 1987; Marion et al. 1993). Calcareous soils may exhibit similar physical effects on root penetration, water infiltration, and gas exchange as compacted soils, in addition to adverse chemical effects.

The relationship between calcareous soils and rooting depth may be difficult to isolate from the effects of fine-textured materials on rooting depth. Root penetration was shown to be impeded on calcareous basal till relative to coarse textured calcareous soils (Mueller and Cline 1959). Within the calcareous till, rooting depth was shallower on poorly drained than on well drained soils. In a comparison of root growth on calcareous and acidic soils, without restrictive layers, total root mass was greater but fine root biomass was lower on calcareous soils than on acidic soils (Badibanga et al. 1992). Roots were also more evenly distributed through the microtopographical features on the calcareous soil.

In a comparison of aggregate stability in soils derived from different parent materials and under different land uses, Tippkötter (1994) found that forest soils of limestone origin had the greatest proportion of aggregates in the mesoaggregate (60–2000 $\mu$m) class. More dispersive energy was required to rupture the aggregates of the limestone derived soils than aggregates of other soils. Carbonate-organic matter associations result in the formation of highly stable microaggregates in calcareous soils (Oyonarte et al. 1994).

### Soil Biological Limitations

High soil $NO_3^-$ concentrations in calcareous soils may reduce mycorrhizal development in pine species (Richards and Wilson 1963). Reduced mycorrhizal growth on alkaline soils in the presence of $NO_3^-$ was attributed to reallocation of the soluble carbohydrates required for mycorrhizal growth and not to adverse effects of $NO_3^-$ or high pH (Richards 1965). Species with limited $NO_3^-$ reductase activity may be more sensitive to disturbed N nutrition than species accustomed to $NO_3^-$ uptake (le Tacon 1978). Microbial biomass was found to be P limited on calcareous soils but not on more acidic soils (Scheu 1993).

## Suitability of Calcareous Soils for Forestry

### Land and Soil Classifications

There appears to be a widely held view that tree species, particularly conifers, do not grow well on calcareous soils in North America. Much of the information supporting this view comes from coarse-scale land inventories and soil capability maps.

The Canada Land Inventory designates soils with excessive carbonates as conferring moderately severe (Class 4) to severe (Class 5) limitations to the growth of commercial forests (Canada Land Inventory 1970). Land Capability for Forestry maps in southeastern British Columbia recognize limitations due to excessive levels of calcium and nutritional problems associated with high levels of carbonates at the subclass level (Subclass L) (Canada Land Inventory 1971; 1972a, b; Canada Land Inventory 1973).

Soil survey reports from The Pas and Ste. Rose du Lac areas in west-central Manitoba also have Subclass L denoting nutritional problems associated with high levels of carbonate within the Soil Capability for Forestry Classes (Mills and Smith 1981; Hopkins and Smith 1982). They indicate that the effect of carbonates is to restrict soil profile development, inhibit weathering of non-calcareous coarse fragments, restrict the depth of soil organic matter accumulation, and result in nutritional problems.

One of the few examples relating soil carbonates to forest productivity comes from the Hinton–Edson Soil Survey (Dumanski et al. 1972). A Forestland Capability Index for Lodgepole Pine was developed, which encompassed soil and productivity factors. Interpretations for lodgepole pine productivity due to carbonates are shown in Table 3. Carbonates were also encompassed in the Index by designation of the factor "t" (toxicity), indicating excessive lime in the rooting zone impeding growth of desirable tree species. Productivity of lodgepole pine was reduced by 36% on the Marlboro Soil Association due to the presence of calcareous soils (Dumanski et al. 1972).

### Occurrence of Natural Stands on Calcareous Soils

Early investigations into the successful establishment of forest species on calcareous soils were

**Table 3. Forest productivity interpretations from the Hinton–Edson Soil Survey** (Dumanski et al. 1972)

| pH class | pH range | Forest productivity adjustment factor |
|---|---|---|
| Strongly acid | 5.1–5.5 | Decrease by 5% |
| Medium acid | 5.6–6.0 | Increase by 20% |
| Slightly acid | 6.1–6.5 | No adjustment |
| Neutral | 6.6–7.3 | Decrease by 10% |
| Mildly alkaline | 7.4–7.8 | Decrease by 20% |
| Moderately alkaline | 7.9–8.4 | Decrease by 30% |

Source: Dumanski, J.; Macyk, T.M.; Veauvy, C.F.; Lindsay, D. 1972. Soil survey and land evaluation of the Hinton–Edson area, Alberta. Univ. Alberta, Dep. Ext., Edmonton, Alberta. Alta. Soil Surv. Rep. 31.

based on observations of natural stands on calcareous soils and the apparent health of the trees. Beech (*Fagus sylvatica* L.) has been the most widely studied species in European forests (for example, Olsen 1943; Day 1946; Avery 1958; Toutain and Duchaufour 1970), although the distribution of some conifers (*Pinus*, *Larix*, and *Picea* spp.) on calcareous soils in Europe has also been investigated (Lavagne and Moutte 1963; le Tacon 1978). Balsam poplar (*Populus* spp.) was found to thrive on exposed marl beds in Wisconsin (White and Wilde 1940).

Coniferous stands have been found on highly calcareous soils in western Canada. For example, Douglas-fir, lodgepole pine, and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) are found on soils that are calcareous at a 12-cm depth in southeastern B.C. (Dykstra and Curran 2000). Stoeckeler (1938) observed white spruce (*Picea glauca* [Moench] Voss) stands on highly calcareous soils in Manitoba (pH 8.4 at 43 cm depth). Coniferous forests are found on calcareous soils in many locations throughout western Canada. However, the conditions under which productivity may become limited is not known. Factors controlling conifer productivity on calcareous soils are currently under investigation in southeastern B.C. (Curran 1999).

### Afforestation on Calcareous Soils

Studies in North America and Europe have evaluated the survival and growth of different tree species on calcareous soils for purposes of afforestation or site rehabilitation. Table 4 lists species that were successfully established as seedlings on calcareous soils. Determining the success or failure of these species as planting stock was the primary purpose of these studies, and generally little attempt was made to determine the mechanisms involved. The exception to this is Erdmann (1966), who determined that depth to carbonates was the most important factor controlling plantation success. In some studies, multiple species were compared to determine relative success, while in others only a single species was considered. Soil pH values and depth to carbonates are indicated where available.

## Factors Correlated with the Establishment and Growth of Trees on Calcareous Soils

### Soil Factors

Few studies of tree growth on calcareous soils have attempted to identify the soil properties responsible for limitations in tree growth or productivity. Where soil properties have been considered, two factors appear to be consistently involved: depth to soil carbonates and soil carbonate content.

The available information indicates a positive relationship between depth to carbonates in the soil profile and tree growth. Early investigations correlated productivity and depth to carbonates in coniferous stands in western Canada. Red pine (*Pinus resinosa* Ait.) height growth increased with increasing depth to calcareous material in southeastern Manitoba (Haig and Cayford 1960). Tree growth was impaired where carbonates were found above 38 cm in the soil profile. Similarly, lodgepole pine dominant height was positively correlated with depth to carbonates in west-central Alberta (Duffy 1964). The relationship was determined for sites with carbonates from 25 to 150 cm from the soil surface.

Depth to carbonates was also found to be an important factor in the growth of lodgepole pine and spruce in the East Kootenays of southeastern B.C. (Kishchuk et al. 1999). Both pine and spruce height and diameter increased with increasing depth to carbonates. Growth of lodgepole pine was reduced where carbonates occurred within the upper 40 cm of soil. Dykstra and Curran (2000) found that tree height and diameter on rehabilitated skid roads in southeastern B.C. were greater on side-cast berms of non-calcareous material than on adjacent undisturbed soils with carbonates within 12 cm of the surface. Differences in tree growth between berms and undisturbed soil was greater at a calcareous site than at non-calcareous sites.

Depth to carbonates was identified as a factor in the degree of success of plantation species on calcareous soils in Iowa (Erdmann 1966). The depth at which carbonates impaired growth (from 30 to 76 cm) varied with species. Depth to carbonates was found to be a discriminating factor in site suitability for red oak (*Quercus rubra* L.) in France (Meredieu et al. 1996). Rooting depth was at least 120 cm and carbonates occurred at a depth of 150 cm.

Soil pH in calcareous horizons was identified as a key factor in site suitability for reforestation in Spain (Sánchez-Marañón et al. 1996). A pH increase from 7.8 to 8.0 appeared to have a negative impact on tree growth. Depth to soil carbonates was found to be an important factor in plantations of *Pinus*, *Cedrus*, and *Cupressus* spp. in Argentina, although depth to carbonates was not separated from depth to C horizon (Ares 1993). Many studies indicate

**Table 4. Tree species successfully established as seedlings on calcareous soils**

| Species | Location | Soil pH | Uppermost depth of soil containing carbonates (cm) | Reference |
|---|---|---|---|---|
| *Pinus banksiana* | Ontario, Canada | n.a.[a] | n.a. | Mullin and Campbell 1975 (m)[b] |
| | Iowa, USA | n.a. | 0 | Erdmann 1966 (m) |
| *Pinus ponderosa* | Iowa, USA | 6.4–7.4 | 0 | Erdmann 1966 (m) |
| *Pinus sylvestris* | Iowa, USA | 8.1–8.6 | 0 | Erdmann 1966 (m) |
| *Pinus strobus* | Iowa, USA | n.a. | 91 | Erdmann 1966 (m) |
| *Pinus resinosa* | Iowa, USA | 6.2–6.7 | 0–23 | Erdmann 1966 (m) |
| *Pinus taeda* | Alabama, USA | 7.1 | n.a. | Jain et al. 1989 (s)[c] |
| *Picea glauca* | Ontario, USA | n.a. | n.a. | Mullin and Campbell 1975 (m) |
| *Picea pungens* | Saskatchewan, Canada | 7.6 | 0 | Carter 1986 (s) |
| *Larix decidua* | Iowa, USA | 7.8 | 0 | Erdmann 1966 (m) |
| *Thuja occidentalis* | Ontario, Canada | n.a. | n.a. | Mullin and Campbell 1975 (m) |
| | Iowa, USA | 8.1–8.6 | 0 | Erdmann 1966 (m) |
| *Pseudotsuga menziesii* | Switzerland | 8 | n.a. | Motschalow 1988 (m) |
| *Populus alba* | Durham County, United Kingdom | 8 | Limestone mine spoil | Richardson and Evans 1987 (m) |
| *Alnus* spp. | Durham County, United Kingdom | 8 | Limestone mine spoil | Richardson and Evans 1987 (m) |

[a] n.a. = data not available.

[b] Comparison of multiple species.

[c] Single species considered.

soils with carbonates at any depth as calcareous; however specific information on the actual depth to carbonates improves the interpretation of relationships to tree growth. It is difficult to isolate the effects of depth to carbonates from the effects of soil density in some calcareous soils (Mueller and Cline 1959; Armson and Williams 1960; Lavagne and Moutte 1963).

Carter (1981, 1987) indicates that disruptions to growth and nutrition of *Populus*, *Salix*, and *Larix* spp. are expected at active carbonate contents of >7%. Total carbonate contents greater than 4 to 7% are associated with growth reductions in *Eucalyptus* spp. (Karschon 1956; Singh 1993). Soil carbonate content was positively correlated with increased crown transparency (loss of foliage) in European *Picea*, *Abies*, and *Fagus* spp. (Webster et al. 1996).

Climatic factors such as precipitation rate and wind patterns determining eolian deposition will directly control calcareous soil properties. These factors may also be correlated with productivity but have not specifically been investigated.

### Genetic Factors

There appear to be differences among species in establishment success, nutrient status, and growth on calcareous soils. For the genus *Eucalyptus*, calcareous and acidic species have been identified. For other species, calcareous and acidic populations have been identified. Reciprocal transplants of one species or population to the opposing soil have been established to determine the role of genotype in performance on calcareous soils. These trials have been carried out in *Eucalyptus* (Parsons and Specht 1967; Anderson and Ladiges 1982; Haridasan 1985), beech (LePoutre and du Cros 1979), and white spruce (Teich and Holst 1974; Xie et al. 1998). Xie et al. (1998) found that spruce originating from calcareous soils exhibited better survival and growth than those from more acidic soils on either soil type. However, spruce grew better on acidic soils regardless of their origin. Results from such studies are difficult to interpret because it is difficult to hold all factors common except for the genotypic group.

## Disturbance of Calcareous Soils in Forest Practices

Some degree of soil disturbance will inevitably result from forest practices (Nambiar 1996). Due to the specific chemical problems associated with calcareous soils, harvesting and site preparation must be undertaken with caution on these soils to minimize impacts and prevent soil degradation (Smith 1988).

Depth to soil carbonates has been identified as a significant factor in the growth of trees on calcareous soils. Consequently, forest practices resulting in the displacement and redistribution of calcareous subsoils are of particular concern. Displacement of calcareous subsoils results from road construction, pushover logging and stump removal for root-rot control, and scalping or gouging (Smith 1988; Smith and Wass 1985, 1994b; Utzig and Walmsley 1988; Dykstra and Curran 2000; Quesnel and Curran 2000).

Soil displacement results in the exposure and mixing of unweathered, calcareous subsoils with neutral or slightly acidic surface horizons (Smith 1988). Displacement and mixing increases the pH of surface materials and may physically remove the forest floor nutrient pool (Smith and Wass 1985; Utzig and Walmsley 1988). Increased soil pH and exposure of calcareous materials may result in decreased nutrient availability and seedling growth (Utzig and Herring 1975; Utzig and Walmsley 1988; Smith and Wass 1994a). Negative effects of increased pH on nutrient availability are intensified on burned sites, and may increase the length of disturbance effects (Utzig and Walmsley 1988; Brockley et al. 1992).

The negative effects of soil displacement by stump removal during pushover logging for root-rot control may outweigh the potential benefits on calcareous soils (Hall and Curran 1999; Quesnel and Curran 2000). Over 25% of the sampling points in a pushover logging trial showed exposure and surficial deposition of calcareous subsoil (Quesnel and Curran 2000). Hall and Curran (1999) established a leaching experiment to determine changes in soil pH under calcareous deposits in association with pushover logging on calcareous soils. The pH of the forest floor underlying calcareous deposits drastically increased over simulated one-year and five-year periods of leaching (Fig. 1).

Soil disturbance on calcareous soils by harvesting and site preparation superimposes adverse chemical conditions on physical effects, particularly for fine-textured soils susceptible to compaction (Smith and Wass 1979, 1994a; Curran 1999). Growth reductions associated with soil physical properties, such as in skidroad inner tracks, may be exacerbated in the presence of carbonates (Smith and Wass 1994a). Where the degree of soil physical disturbance is less severe, as in a stumping operation, the exposure of calcareous soil may still cause significant growth reductions (Smith and Wass 1994b). The British Columbia Ministry of Forests (1995) uses the presence of appreciable carbonates as a criterion for assessing soil and forest floor displacement hazards.

## SUMMARY

Calcareous soils originate with carbonate-rich parent materials. These soils have inherent properties that are altered through the processes of soil development. They are formed on a variety of surficial landforms and may support a variety of forest types. The chemistry of calcareous soils is complex, and it is influenced by biological activity and soil physical properties.

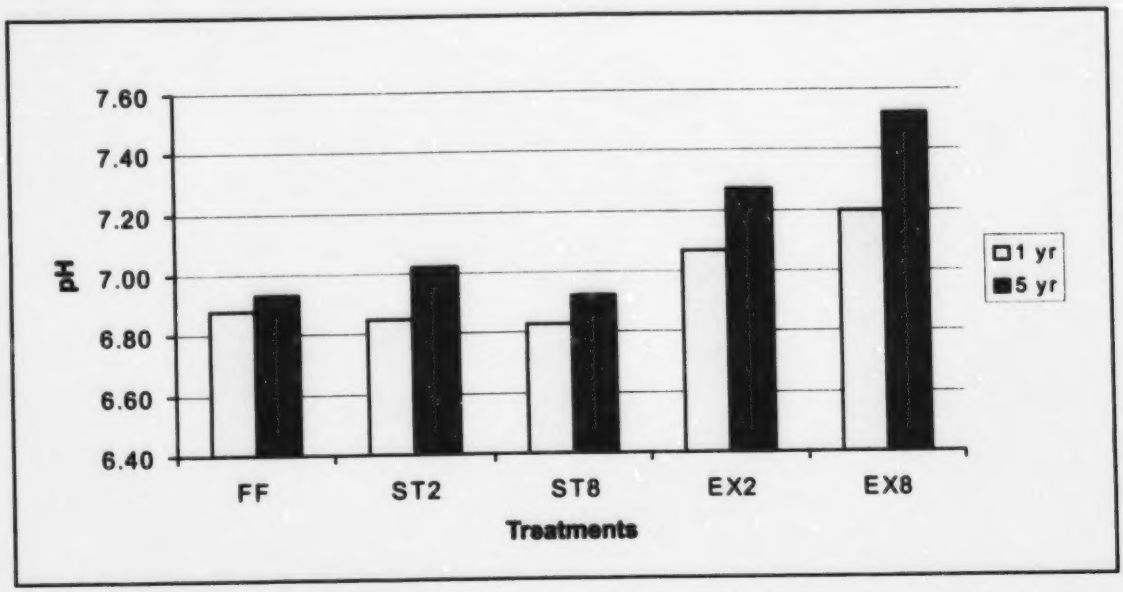


**Figure 1. Forest floor pH after leaching in laboratory, equivalent to 1 or 5 years in the field.** (FF = forest floor alone; ST2 = under 2 cm strongly calcareous deposit; ST8 = 8 cm; EX2 = 2 cm extremely calcareous deposit; EX8 = 8 cm; from Hall and Curran 1999).

There are potential chemical, physical, and biological limitations to forest productivity on calcareous soils. Chemical limitations are related to the stabilization of soil organic matter and to nutritional deficiencies, excesses, or imbalances. Physical limitations are related to soil aggregation, cementation, compaction, and crusting. Biological limitations are associated with mycorrhizal development and microbial biomass nutrient dynamics.

Growth reductions in conifers on calcareous soils have been observed; however, there are also instances where conifers appear to be growing adequately on calcareous soils. Soil, site, and species properties that may favor or inhibit establishment and growth of conifers on calcareous soils must be evaluated to determine the factors controlling growth and productivity. Depth to soil carbonates appears to be the factor most consistently related to growth reductions, but further investigation is required.

Disturbance and displacement of calcareous soils under forest operations can profoundly change the soil environment. These changes will be of concern if they adversely affect tree establishment and growth through changes in physical or nutritional properties.

Despite the potential limitations to tree growth on calcareous soils, documented instances of growth reduction are scarce, particularly for conifers. Controlled experiments to compare conifer productivity on calcareous and non-calcareous soils are lacking in the literature. There is currently limited information that can be applied directly to forest management on calcareous soils in southeastern B.C. and western Alberta. More information on the effects of calcareous soils on tree growth and the mechanisms by which growth may be affected is required to make management decisions such as species choice or acceptable levels of soil disturbance. These issues are currently under investigation by researchers in B.C. and Alberta through retrospective studies, compilation of existing data, and development of field trials. Further information about ongoing work in southeastern B.C. in the Invermere Forest District Enhanced Forest Management Pilot Project can be found at

<http://www.for.gov.bc.ca/nelson/district/invermer/Pilot/index.htm>.

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# APPENDIX 1
# DISSOLUTION REACTIONS OF CARBONATE AND FACTORS CONTROLLING CARBONATE DISSOLUTION

The chemistry of calcareous soils is controlled by the dissolution and re-precipitation of $CaCO_3$. Assuming a system with only $CaCO_3$ present (as calcite), dissolution and precipitation occur in the following manner:

1. $CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-}$,
2. $CO_3^{2-} + H_2O \rightleftharpoons HCO_3^- + OH^-$, and
3. $OH^- + CO_2 \rightleftharpoons HCO_3^-$.

Reactions 1 to 3 are summarized as

4. $CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{2+} + 2\,HCO_3^-$.

The dissolution of $CO_2$ to carbonic acid ($H_2CO_3$) is summarized as

5. $CO_{2(g)} + H_2O_{(aq)} \rightleftharpoons H_2CO_{3(aq)}$.

The net reaction is

6. $CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{2+} + 2\,HCO_3^-$.

Reactions are taken from Thorne and Seatz (1955), van Breeman and Brinkman (1978), Jenny (1980), Bruckert and Rouiller (1982), and Birkeland (1984).

The partial pressure of carbon dioxide ($pCO_2$) regulates pH and bicarbonate ($HCO_3^-$) concentration, and strongly influences the soil solution chemistry in calcareous soils (Yaalon 1957; Johnson and Cole 1980; Loeppert 1986). Carbon dioxide is produced during organic matter decomposition and respiration by roots and microbial biomass, resulting in much higher $pCO_2$ in soils than in the atmosphere (Talibudeen 1981; Kinzel 1983). The volumetric concentration of $CO_2$ in the soil atmosphere ranges from 0.2% to 10% (Bradfield 1941; Yaalon 1957), in comparison with the atmospheric $pCO_2$ of 0.035% (Bruckert and Rouiller 1982).

Dissolution of $CaCO_3$ occurs as $pCO_2$ increases, pH decreases, or unsaturated water moves through the soil (Birkeland 1984; Pomazkina et al. 1996). An indefinite rise in pH by carbonate dissolution is offset by the reaction of hydroxyl ions ($OH^-$) with $CO_2$ (Bruckert and Rouiller 1982). However, at low $pCO_2$, soil pH may increase as pH becomes more sensitive to changes in $pCO_2$ (Thorne and Seatz 1955; Russell 1973). Precipitation of $CaCO_3$ occurs as $pCO_2$ decreases, pH increases, the soil solution becomes Ca and $HCO_3^-$ saturated, or water content decreases due to evaporation or decreased infiltration (Birkeland 1984).

The greatest $pCO_2$ would be expected to occur in the surface horizons with high biological activity (Birkeland 1984). High $pCO_2$ is also favored by the low diffusivity of $CO_2$ in soil, particularly in fine-textured soils (Johnson and Cole 1980). Movement of water into zones of high $pCO_2$ favors $H_2CO_3$ formation and the dissolution of $CaCO_3$ (Johnson and Cole 1980; van Breeman and Brinkman 1978). In surface horizons there may be sufficient downward water movement to reduce $pCO_2$ by formation and leaching of $HCO_3^-$ (Birkeland 1984). Precipitation of $CaCO_3$ and formation of calcareous horizons lower in the soil profile occurs where $pCO_2$ is decreased, Ca and $HCO_3^-$ reach saturation concentrations, and water percolation is restricted (Birkeland 1984).

The foregoing discussion describes the relatively simple situation where calcite is the only solid phase component. The solubility of calcite is controlled by temperature and the presence of other ions in solution, as well as by $pCO_2$ and water (Talibudeen 1981). In real soil systems, the soil solution composition is influenced by products of organic matter decomposition, the presence of carbonates containing metal cations other than Ca (Novozamsky and Beek 1978; Bui et al. 1990), the reactive particle surface area (Moore et al. 1990), adsorption of cations on calcite surfaces (Talibudeen 1981), uneven distribution of solid carbonate particles within the soil matrix (Ulrich 1983), and spatial variations in $pCO_2$ and the soil physical properties associated with gaseous exchange (Bruckert and Rouiller 1982).

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# APPENDIX 2
# METHODS FOR DETERMINATION OF CARBONATE REACTIVITY AND CARBONATE CONTENT OF SOILS

## Carbonate Reactivity

The simplest assessment of carbonate reactivity is by physical determination of particle size distribution and determination of carbonates in the clay fraction (Yaalon 1957). Effective particle size distribution accounts for surface area and surface reactivity and is determined using carbonate dissolution rates (Moore et al. 1990). An indirect measure of carbonate particle size and surface area is obtained by determination of active carbonates, which precipitate as calcium oxalate in an ammonium oxalate solution (Carter 1981). Carbonate reactivity parameters are compared in del Campillo et al. (1992), and the effect of soil dispersion treatments on reactivity determinations are discussed in Hartwig and Loeppert (1991).

## Carbonate Content

Methods for determining the quantity of inorganic carbonates in soils are described in Nelson (1982), Chaney et al. (1982), and Loeppert and Suarez (1996). Determinations are either for carbonates or for Ca, which assumes negligible quantities of Mg carbonates (Chaney et al. 1982). There are three types of methods: acid dissolution of carbonate and determination of carbon dioxide ($CO_2$) evolved, acid neutralization of carbonates and back titration of excess acid, and determination of the Ca and Mg in an acid leachate (Nelson 1982). A comparison of several methods for carbonate determination was done by McKeague and Sheldrick (1976). Quantities of individual carbonate minerals (for example, calcite and dolomite) are determined by X-ray diffraction, electron microscopy, and differential dissolution rates (Nelson 1982; Bui et al. 1990). Carbonate concentrations of soils range from traces to >80% (Loeppert et al. 1994).

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